Diagnosis of meridional transport of ozone and related species using a global chemical transport model

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D. List of symbols

論文内容要旨

The purpose of this study is to clarify the mechanisms of constituent transport and mixing processes in the stratosphere and troposphere. For this purpose, three-dimensional distributions of ozone and related species are reanalyzed with a Chemical Transport Model (CTM). A new diagnostic tool for meridional constituents transport is developed and used to provide dynamical insight into the problems of atmospheric transport. Using this, detailed analyses are made of mean-meridional and eddy transports of minor constituents and their seasonal variations.

In the ozone reanalysis system, three-dimensional constituent fields, including ozone, are reproduced by the CTM coupled to a General Circulation Model (GCM) that nudges atmospheric objective analyses of ERA40. First, in order to improve performance, we make a sensitivity experiment of reanalyzed ozone to changing meteorological variables to be assimilated into the GCM. Two experiments were performed; one nudges only horizontal wind (mechanical nudging), and the other nudges both horizontal wind and temperature (mechanical and thermal nudging). The two experiments show significantly different ozone field, due to the cold bias of the GCM. Mechanical nudging causes weaker meridional circulation in the lower stratosphere and a stronger circulation in the troposphere, compared to the ERA40. Thermal nudging causes a spurious heat source from the systematic errors in the GCM, which makes the meridional circulation stronger in the lower stratosphere and weaker in the troposphere. The meridional circulation of the nudged GCM and reanalyzed ozone filed depend considerably on the relaxation time for the thermal nudging.

Second, a diagnostic tool is proposed to analyze the meridional constituent transport, where the mean-meridional transport equation is formulated based on mass weighted isentropic zonal means. In comparison with the conventional methods, the present diagnosis is shown to have advantages for the expression of both the mean and eddy transport terms. The adiabatic eddy flux is separated from the diabatic eddy flux, which is parallel to the isentropic surface. The analysis shows that the eddy flux is almost adiabatic except that it is significantly affected by diabatic effects near the lower troposphere. Another advantage lies in the mean meridional transport. Although it is almost similar to the transformed Eulerian mean (TEM), significant differences can be found near the Antarctic polar vortex due to nongeostrophic effects. Furthermore, the isentropic diagnosis expresses a strong equatorward flux near the lower boundary, while the TEM hardly does this because of inadequate treatment of the lower boundary conditions. This diagnosis method enables us to get better insight into the meridional transports.

By using the new diagnostic tool, mean-meridional transport and mixing processes are analyzed from reanalyzed dynamical and thermodynamical fields and constituent fields;

The life cycle of ozone can be understood through the exact estimation of the transport terms. Although the stratospheric meridional transport is mainly performed by the Brewer-Dobson circulation, the strong poleward eddy ozone flux is caused by planetary wave breaking, especially in the winter hemisphere. In the extratropical lower stratosphere and upper troposphere, the ozone subsides due to mean downward motions and is diffused to the lower latitudes probably due to baroclinic waves. These eddy fluxes appear to be separated into two streams along the isentropic surfaces in the mid-latitudes, equatorward-upward flux in the lower stratosphere and equatorward-downward flux in the upper troposphere. Near the surface, large equatorward transport appears due to strong meridional flows and effectively lost through chemical processes around the subtropics.

Seasonal variations of the meridional ozone transport and their contributions to the total ozone amount are also investigated. The stratospheric poleward mean ozone transport decreases the total ozone amount in the tropics and increases it in the extratropics. The mean ozone flux convergence is centered near the pole in the northern hemisphere and has considerable seasonal variation with a maximum in late winter. In the southern hemisphere it is centered outside of the polar vortex with weaker seasonal variation. Seasonal variation of the tropical divergence is also caused by the Brewer-Dobson circulation, which is greatest in the northern winter. The eddy ozone transport is mostly equatorward in the lower stratosphere and troposphere, since the extratropical downward transport forms the isentropic poleward gradient of the ozone mixing ratio. An exception is that a strong poleward eddy transport increases the total ozone amount near the Antarctic in late spring. The transport characteristics are discussed in detail during and after the breakdown of the Antarctic polar vortex.

Meridional eddy transports of minor constituents are sometimes characterized by isentropic horizontal diffusion coefficients. A systematic survey of the commonality and constituent dependency of the diffusion coefficient enables us to investigate the general aspects of atmospheric mixing processes. Long-lived species have common seasonal and latitudinal variations of diffusion coefficients, which suggest commonality of the linear flux-gradient relationship. The diffusion coefficients for lifetimes shorter than 10^6 sec become considerably greater than those for long-lived species and indicate the significance of nonlinear effects. Shorter lifetimes also result in greater ratio of the eddy to the mean meridional transports.

The stratospheric constituent gradients are large at the subtropics and polar vortex edges. They evolve through the vertical advection and isentropic mixing in the stratosphere. The meridional shear of the mean vertical motion mainly produces the subtropical edges with gradient maxima in early spring and early autumn. The subtropical edge is more clearly seen in the upper stratosphere than in the lower stratosphere. Isentropic mixing has two effects; producing the meridional constituent gradient due to its stairstep effect, reducing the curvature of constituent slopes and the meridional constituent gradient. Its reducing effect makes the subtropical edges unclearer in the decay phase of the subtropical edge, particularly from late autumn to late winter. In contrast to the subtropics, the producing effect of isentropic mixing effectively steepens constituent gradient near the Antarctic polar vortex edge, particularly in the lower stratosphere.

論文審査の結果の要旨

宮崎和幸の研究目的は，オゾンを始めとする大気微量成分の子午面輸送機構を解明することである。

輸送解析には大気微量成分の精密な3次元データを利用するため，最初に，気象研究所で開発された大気微量成分再解析システムの改良に取り組んだ。微量成分の再解析には大気大循環モデルに結合された化学輸送モデルを用いる。日々の大気状態を忠実に再現するため，ニュートン強制によりモデル大気を客観解析に近づける。大気大循環モデルを利用することによって運動場や微量成分分布の力学的整合性を高めることができる。しかしながら，大気大循環モデルが気温のバイアスを持つと，客観解析との不整合により，輸送量に系統的な誤差を生じる。本研究では，強制項の緩和時定数を運動方程式と熱力学方程式で独立に調整することにより，輸送の誤差を最小限に抑えることができることを示した。

次に，子午面輸送の新しい解析ツールを開発した。これは温位面での質量荷重帯状平均に基づき平均輸送と渦輸送を定義するものである。気圧面での帯状平均に基づく従来の方法と比べると，準地衡風近似を仮定せずに平均流輸送を評価できること，下部境界を正しく扱えること，物理的イメージが明快で渦輸送の評価も容易であること，などの利点がある。

新しい解析ツールを用いて，オゾンを始めとする大気微量成分の輸送メカニズムを解析した。その結果，平均流による輸送では下部境界付近や極渦周辺で従来とは異なる結果を得た。また，成層圏のオゾンの渦輸送に関してはほぼ等温位面に沿う断熱過程が支配すること，これに対し対流圏下層の渦輸送では温位面との交差が見られ非断熱効果が認められること，また渦輸送が上部成層圏では極向き下部成層圏と対流圏では赤道向きであることなどを見出した。輸送と光化学生成消滅に関する知見を整理しオゾンのライフステージを明らかにした。そのほか，詳細な輸送解析から，亜熱帯や極渦縁辺の輸送障害壁が微量成分分布に及ぼす影響などを明らかにした。

宮崎和幸はこのように大気微量成分研究のインフラとなる再解析の精度向上に貢献するとともに，新しい輸送解析ツールを開発し，大気微量成分の輸送メカニズムに関する新しい知見を得た。これらの成果は自立して研究活動を行うに必要な高度の研究能力と学識を有することを示している。したがって宮崎和幸提出の博士論文は，博士（理学）の学位論文として合格と認める。